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MATERIALS AND FABRICATION METHODS FOR
DEPLOYABLE THIN FILM STRUCTURES USED IN
SPACE OPERATIONS

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1. INTRODUCTION

A number of possible future space missions will require large, deployable surface areas for the purpose of intercepting electromagnetic radiation. Lightweight thin film structures in space may be used for reflection and collection of rf energy, for shadow shields to control spacecraft temperature, or for utilizing photon pressure for propulsion and attitude control (solar sails).

This program is addressed specifically to a solar-sail concept (Refs. 1, 2) in which thin, relatively narrow reflector strips are used. These are stowed on simple rolls and are deployed and stabilized by rotational motion of the spacecraft ("Heliogyro"). Figure 1, taken from Reference 1, shows the mode of operation of the Heliogyro concept as it is applied to an experimental spacecraft.

In this report, basic materials requirements and fabrication concepts for solar-sail surface structures are discussed. The state of the art for industrially produced thin films is reviewed, and exploratory laboratory experiments with metallic ultrathin film materials are described.

2. CHARACTERISTICS OF SOLAR-SAIL SURFACES

2.1 Mass Properties of Solar Sails

The ratio between the radiation force and the force due to the sun's gravitational field is used as a figure of merit for the solar-sail surface. For ideally reflecting surfaces exposed to normally incident sunlight, this figure of merit equals the "sail lightness number", λ_s (Ref. 1),

$$\lambda_s = \frac{p_o}{a_s\, m''}$$

where $p_o = 0.9 \times 10^{-5}\ N/m^2$ is the solar pressure of normally incident sunlight upon an ideally reflecting surface at 1 AU (i.e., at the Earth's distance) from the sun

$a_s = 0.60 \times 10^{-2}\ m/sec^2$ is the acceleration in the sun's gravitational field at 1 AU

m'' = the surface mass density of the solar sail.

We note that the fraction, $p_o/a_s = 1.5\ gr/m^2$, is independent of the distance from the sun.* Previous studies indicate that useful photon thrust can be obtained with sail lightness numbers larger than approximately $\lambda_s = 0.1$. Thus the mass/unit area of the solar sail must be restricted to values less than approximately 15 gr/m^2. The corresponding film thicknesses for typical materials are listed in Table I.

Film materials that are thinner than the limiting values listed in the table are designated as "ultrathin" materials for the purpose of this study.

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* Note: For convenience, the mixed metric unit "grams/square meter" (1 $gr/m^2 = 2.02 \times 10^{-4}\ lb/ft^2$) will be used in this report. Film thicknesses will be given in microns (1 μ = 10^{-6} m = 0.0394 mil)

TABLE I. LIMITING MATERIALS THICKNESS FOR $\lambda_s \geqq 0.1$

Material	Density (gr/cm^3)	Thickness μ	(mils)
Polymer films:			
Polycarbonate	1.21	12.4	0.49
Polyester	1.40	10.7	0.42
Fluorocarbon	2.15	7.0	0.28
Metals:			
Aluminum	2.7	5.6	0.22
Titanium	4.5	3.3	0.13
Nickel	8.9	1.7	0.07

2.2 Optical Properties of Solar Sails

For real surfaces, the figure of merit must include the optical surface characteristics of the sail (Fig. 2),

$$\lambda_s' = \lambda_s f_r$$

where f_r is a "reflection coefficient" which accounts for the loss of thrust due to imperfect reflectivity of the solar sail. For a reflector which is in thermal equilibrium, it can be described by

$$f_r = 1/2 \left[(1 + k_R) R + (1 - k_T) T + (1 + \Delta_E) A\right]$$

where

R, T, and A are the energy fractions which are reflected, transmitted, and absorbed, respectively;

k_R and k_T account for the angular intensity distribution of the diffuse portion of reflected and transmitted energy;

and

Δ_E accounts for any differential between front and backside in the absorbed and thermally reemitted radiation. (Such a differential can originate from differences in surface emissivity, surface temperature, or angular distribution of emitted radiation).

For good reflectors, the specular reflectance will normally dominate ($k_R \sim 1$) and scattering of transmitted light in thin films is usually small ($k_T \sim 1$). If it is further assumed that front and back surfaces emit equally ($\Delta_E = 0$), then the equation for the reflection coefficient reduces to

$$f_R = R + \frac{A}{2}$$

Figure 3 shows the reflectance of three typical deposited metal reflector coatings in function of wavelength (Ref. 3) and the solar spectral energy distribution (Ref. 4).

Table II shows the reflected energy fraction, R , calculated from the spectral reflectance distributions given in Reference 3 and the corresponding reflection coefficient for several metallic coatings.

TABLE II. OPTICAL PROPERTIES OF METAL REFLECTORS

Material	Solar Reflectance	f_R
Silver	0.954	0.977
Aluminum	0.920	0.960
Copper	0.816	0.908
Gold	0.794	0.897
Rhodium	0.813	0.906
Platinum	0.754	0.877

The data given in Table II refer to freshly deposited, smooth metal surfaces, prepared on polished substrates. In the case of mat surfaces, a significant decrease in reflectivity is observed. Reference 5 gives the solar absorption of aluminum foil as ranging from 0.15 to 0.35, depending on surface finish. Thus, long-term exposure to space environment may reduce the reflection coefficient of high-quality metal reflectors significantly.

For very thin metal films, transmission and absorption of light become significant fractions. Further reduction of film thickness yields no increase in the figure of merit, λ', because of rapidly decreasing reflecting coefficient. Table III lists data for thin, deposited aluminum films at 0.5 μ wavelength, taken from Reference 6, the reflection coefficient (assuming $k_R = k_T = 1$ and $\Delta_E = 0$), and the corresponding theoretical reflector figure of merit, λ', that would be obtained in a free-standing film of the indicated thickness.

TABLE III. OPTICAL PROPERTIES, REFLECTION COEFFICIENT, AND FIGURE OF MERIT FOR THIN ALUMINUM FILMS

Film Thickness (μ)	R	T	A	f_R	λ'
0.005	0.22	0.48	30	0.37	41
0.010	0.68	0.15	17	0.76	42
0.015	0.85	0.05	10	0.90	33
0.020	0.90	0.02	08	0.94	26

From these data it is evident that a theoretical "not-to-exceed" limit for reflector figure of merit in ultrathin reflector films would be approximately 40 and would be reached in free-standing aluminum films 0.01 μ (100 Angstroms) thick. This value for λ' is an order of magnitude better than the best aluminized polymer thin-film reflector material presently available in large quantities. Considerable gain in solar-sail performance, therefore, is in principle possible from advances in thin-metal-film technology.

2.3 Strength Requirements

The rotation of the spacecraft in the Heliogyro solar-sail concept provides the required centrifugal stiffening and and deployment forces for the reflectors.

The specific stress, σ_R/ρ, at the root of a reflector blade with uniform width and uniform surface mass density is related to the circumferential velocity at the blade tip, V_T ,

$$\sigma_R/\rho = \frac{V_T^{\,2}}{2g}$$

The design tip speed for simple Heliogyro designs without blade taper ranges from 300 to 600 ft/sec (Ref. 1). The blade root specific stresses at the spacecraft center of rotation ranges correspondingly from 0.034×10^6 to 0.14×10^6 in. The upper limit yields blade root stresses to 14 ksi in aluminum reflectors and to 7.3 ksi in metallized polymer films.

2.4 Uniformity

Uniformity of thickness (i.e., mass distribution) and reflectivity are important to the Heliogyro design concept since blade pitch control can be severely affected by either center of gravity or center of pressure offset in the blade. Random variations over small areas are not critical; systematic variations across the blade width, however, must be minimized. Careful product quality control and possibly random cutting and splicing of produced thin films may be required to obtain satisfactory uniformity of Heliogyro reflector materials.

3. PRODUCTION METHODS AND MINIMUM GAUGE LIMITATIONS FOR ULTRATHIN FILMS

An exhaustive review of the state of the art in thin-film materials and processing has been conducted. The detailed results of this study have been reported in Reference 7.

Production methods for thin films can be broadly classified into two groups:

- Attenuation of solid ingots by mechanical working, such as rolling, drawing, etc.
- Deposition of film on a substrate either from liquid or vapor phase.

Table IV shows a summary of these processes.

3.1 Attenuation Process

The first group contains the standard methods of thin sheet-metal and industrial polymer-film production. It can be subdivided into two groups (Table IV-A):

- "Hard" processes, where the final dimensions of the film are controlled by a mechanically contacting hard die, roller, etc.
- "Soft" processes, where the gauge is reduced by stretching the material in freely suspended sections.

The hard process is primarily used in the production of metal films (foils). It is basically limited by the required dimensional tolerances of the controlling die and by the required surface smoothness of the roller. Further limitations are imposed by the finite size of unavoidable inclusion in the ingot material and by excessive work-hardening of most metals during the processing.

The present state of the art allows the industrial production of metal foils in gauges to 4.5 μ, and to approximately 2 μ for small quantity processing in relatively narrow widths.

TABLE IV. THIN-FILM PRODUCTION PROCESSES

A. Attenuation Processes:		
"Hard" process	Rolling Drawing Hard die extrusion	
"Soft" process	Flat film (draw extrusion) Tubular film (blow extrusion)	
B. Deposition Processes:		
	From liquid	From vapor
Thermodynamic	Film casting Hot dipping Flame spraying Solvent evaporation Painting	Physical vapor deposition (PVD): Electron beam Laser Resistance R.F. heating Sputtering
Electrochemical	Electroplating	Glow discharge polymerization Reactive sputtering
Chemical	"Electroless" plating Liquid film polymerization Surface catalysis of liquids	Chemical vapor deposition (CVD): Thermal decomposition Hydrogen reduction UV polymerization Surface catalysis of dissociated vapor

The "soft" method is restricted to materials which will provide a stable mechanical attenuation process by "work hardening". This method is widely used in the production of industrial thermoplastic films. Minimum gauge limitations stem primarily from the unavoidable presence of foreign particles in the thermoplastic material. These cause pinholes and subsequent tearing of the film during the attenuation process. A further difficulty arises from electrostatic surface charges generated on the film during this process.

Thermoplastic films are available in commercial quantities in thicknesses to approximately 4 μ, with special products (produced primarily for the capacitor industry) down to approximately 2 μ.

3.2 Deposition

A wide variety of deposition process methods are employed, and almost any material can be deposited as a thin coating by one of these methods. A classification of deposition methods (as shown in TABLE IV-B) can be made by the phase of the starting material (i.e., liquid or vapor) and by the nature of the solidification process (i.e., thermodynamic, electrical, or chemical).

Many of these processes are essentially a molecule-by-molecule condensation; therefore extremely thin film coatings can, in principle, be produced. Minimum gauge limitation of free-standing films rests in the need to separate the deposited films from the substrates.

The removing of deposited films from substrates can be accomplished by either of two methods:

- Mechanical peeling of a weakly adhering film from the substrate
- Removal of substrate by melting or by exposure to solvents.

The first method is limited by the strength of the film. This strength must be sufficient to overcome the adhesive force of the substrate interface. Since the adhesive force is essentially independent of the film thickness, the minimum practical thickness must exceed that which causes the film to tear rather than to peel.

Chemical or thermal removal of the substrate avoids this limitation. This process has been used for the preparation of free-standing deposited submicron film samples (Ref. 3) for many laboratory investigations. The method is generally too unwieldy to be seriously considered for industrial quantity production. Also, the presence of pre-stress in the deposited film and the liberation of interface forces upon chemical substrate removal, may in some cases cause destructively large stresses in the residual film and therefore limit the practically obtainable minimum gauge.

3.3 Handling Limitations

A limitation that applies to all fabrication processes involves the handling difficulties attending the transport, spooling, and unwinding of ultrathin films in a process environment of gravity, electrostatic charges, and unavoidable air currents. This seems to set a "practical" limitation of 1/16 to 1/8 mil nominal gauge, according to most suppliers. The potential of in-space fabrication by automatic processes therefore appears to hold promise in the economical production of ultrathin films. Physical vacuum deposition (PVD) appears to be a suitable candidate for this approach.

4. COMMERCIALLY AVAILABLE ULTRATHIN FILMS

The commercial availability of ultrathin films as defined in Section 2 of this report, was established by the following method:

Material producers and suppliers of thin metallic and polymer films had been previously identified (Ref. 7). Of the supplemented list, those which indicated a delivery capacity for ultrathin films were extracted and their local sales and supply organizations were identified. The purchasing department at Astro Research Corporation was instructed to contact each supplier with a request for fixed price quotation and firm delivery for production quantities of the thinnest available material in maximum available width. Table V lists the results of this survey.

Several comments are pertinent to the results of this survey. It was found that "nominal gauge" quotations were frequently quite misleading and that a more accurate measure of the actual thickness in ultrathin films is the quoted yield (i.e., surface area per unit weight). The mass-per-unit surface, m" , in Table V has, therefore, been calculated from the quoted "yield". It also appears that ultrathin films quoted at a price per square foot tend to be as thin as or somewhat thinner than advertised, whereas films quoted at a price per pound are invariably thicker than would be indicated by either "nominal gauge" or "yield". Caveat emptor!

Producers of thin metal foils who were contacted claim a capability of rolling thin metal films to 1/16 mil gauge in stainless steel, copper, and titanium in widths varying from 3.5 in. to 12 in. No firm price quotation or delivery schedules could be secured for large quantity orders, and it was concluded that these materials were available only on an experimental basis.

The most attractive commercially available material for solar-sail applications uncovered in this review is the polycarbonate, "Kimfol", nominally 1/16 mil (actually 0.08 mil) capacitor-grade film. It is produced under license by the P.J. Schweitzer Division of Kimberly Clark Corporation from a basic polycarbonate resin imported from Bayer in Germany. It is produced in 40-in. width, apparently by a soft extrusion process, and slit to standard roll widths (20 in. maximum)

TABLE V. COMMERCIALLY AVAILABLE ULTRATHIN FILMS

Material Type	Gauge Nominal	Max. Width in.	Quoted "Yield" sq ft/lb	m" gr/m^2	Material Producer	Thin Film or Foil Supplier	Price $ per sq ft	Delivery ARO
Aluminum Type 1145 or 1100	0.175 mil	12	418	11.5	Alcoa	The Malco Co. Huntington Pk Calif.	0.0147	Off stock
Fluorocarbon TFE	1/8 mil	12	676	7.15	Du Pont	Dilectrix Co. Farmingdale, N. J.	0.5000	1 Mo.
Polyester Mylar S	1/8 mil	20	920	5.26	Du Pont	Cadillac Plastics, Huntington Beach, Calif.	0.0333	1 Mo.
Polycarbonate "Kimfol"	1/8 mil 1/16 mil	40 40	1130 1980	4.38 2.45*	Bayer	P.J.Schweitzer Division Lee, Mass.	0.0126 0.0202	Off stock Off stock

* Measured average value from five 8.5 x 11 in. samples: 2.82 gr/m^2

for use in the capacitor industry. This supplier furnishes the same material up to 12.5 in. wide with an aluminum coating of approximately 0.025 μ thickness for capacitor applications. Deliveries of uncoated material are from stock. Shipment of unslit 40-in. width had not been attempted previously because there was no commercial demand for full-width material.

Table VI lists vendor-supplied data on the physical properties of this material.

TABLE VI. PROPERTIES OF "KIMFOL" POLYCARBONATE FILM

Ultimate tensile strength, lengthwise	31,000 psi
Tensile yield strength, lengthwise	11,000 psi
Ultimate elongation, lengthwise	30 to 50%
Ultimate tensile strength, crosswise	11,000 psi
Tensile yield strength, crosswise	10,000 psi
Ultimate elongation, crosswise	160%
Density	1.21 gr/cm^3
Shrinkage at 145°C for 8 hours	1.6%
Dielectric constant	2.8

5. LABORATORY INVESTIGATION

The potential of physical vapor deposition to produce thin, free-standing, reflective films was studied in an exploratory laboratory investigation.

Thin films of aluminum and nickel were deposited on a variety of substrates. The films were subsequently removed from the substrates, and subjected to tensile tests.

The physical vapor-deposition system used in this study is shown in Figure 4. It consists of an 18-in. bell jar with a 6-in. diffusion pump and a 30 ft^3/min fore pump capable of evacuating the cold and clean chamber to 10^{-6} torr. The vacuum system contains two individually controlled 6-kW electron-beam guns, two water-cooled hearths, a substrate holder, and a substrate temperature control heater. A residual gas analyzer (RGA) was used to monitor impurity incidence during some of the depositions.

The electron-beam guns are controlled by a Sloan "Pan Omni" automatic deposition-rate monitor and controller that allows pre-set deposition rates and total film-thickness control. Deposits were made on substrate plates approximately 4 in. x 6 in. Additional experiments were performed in generating "textured" deposits by masking the substrate area with a multiple strip mask shown in Figure 5.

Initial experiments with silicone-oil release agents on metallic substrates were unsuccessful, producing exceedingly weak films. Similarly, experiments with NaCl (rocksalt) substrates dissolved in water after deposition, produced films with excessive amounts of pinholes, probably due to poor initial polish of the substrate surface.

Films and strips of satisfactory quality were produced on clean glass and on oxidized copper substrates. The films could be removed by slight flexing of the substrate, or they fell free upon handling. Satisfactory free-standing films were also produced from copper substrates removed by acid etching in HNO_3. No attempt was made to minimize the thickness of the deposited films in this program.

The films and strips of vacuum-deposited aluminum and nickel were cut into tensile specimens of 0.25 in. width and approximately 2 in. length. The samples were clamped at one end, and dead-weight loading was applied to the free end. Sample weight and breaking load were recorded.

Average sample thickness was estimated from sample weight, surface area, and from the theoretical material specific weight (0.101 lb/in.^{3} for aluminum and 0.330 lb/in.^{3} for nickel). Specific ultimate tensile strength was calculated by multiplying sample length with the ratio of its breaking load and its weight,

$$\text{Specific strength} = \text{length of sample} \times \frac{\text{strength}}{\text{weight}}$$

Table VII lists the pertinent process parameters and test results of selected samples.

The strength data obtained showed considerable scatter, but were generally equal to or higher than the published ultimate tensile strength of the pure metal produced in metallurgical bulk form. The specific strength of the two deposited materials investigated appears to be adequate for solar-sail applications (see Section 2).

TABLE VII. ELECTRON-BEAM VAPOR-DEPOSITED METAL FILMS

Material	Estimated Thickness (μ)	Substrate	Specific Ultimate Strength (10^6 in.)	Deposition Rate (μ/Min.)	Substrate Temp. (^{o}C)	Remarks
Al	6.3	Copper	0.225	0.1 - 0.3	350	HNO_3 etched substrate
Al	7.7	Glass	0.135	0.2 - 0.3	300	Film peeled free, after flexing substrate
Ni	7.1	Glass	0.200	0.4 - 0.3	175	Peels easily from substrate
Ni	7.8	Glass	0.151	0.5 - 0.6	175	Peels easily from substrate

6. CONCLUSIONS

Rolled aluminum foil is available in ~4.5 μ thickness in mill run quantities (1000 lb or more per order). Used as a solar sail, this material will provide a lightness number of approximately 0.13.

Industrially produced polymer films, vacuum-coated with reflective aluminum, have been available for some time with surface mass density of approximately 5 gr/m^2 (nominally 1/8 mil polyester with 0.05 μ aluminum coating on each side). This yields a sail lightness number of approximately 0.3.

Recent development of thin polycarbonate film technology, primarily motivated by the need for compact capacitors, has produced metal-coated dielectric films of nominally 1/16 mil gauge in industrial quantities and in adequate width for solar-sail design. This permits a sail lightness number of approximately 0.5 to 0.6.

The fabrication of free-standing thin metal films by physical vacuum deposition and subsequent chemical or mechanical substrate removal is possible and yields material of adequate mechanical strength. This process lends itself in principle to a continuous and automated space fabrication concept and promises to yield sail lightness numbers considerably larger than those obtainable with aluminized polymer films.

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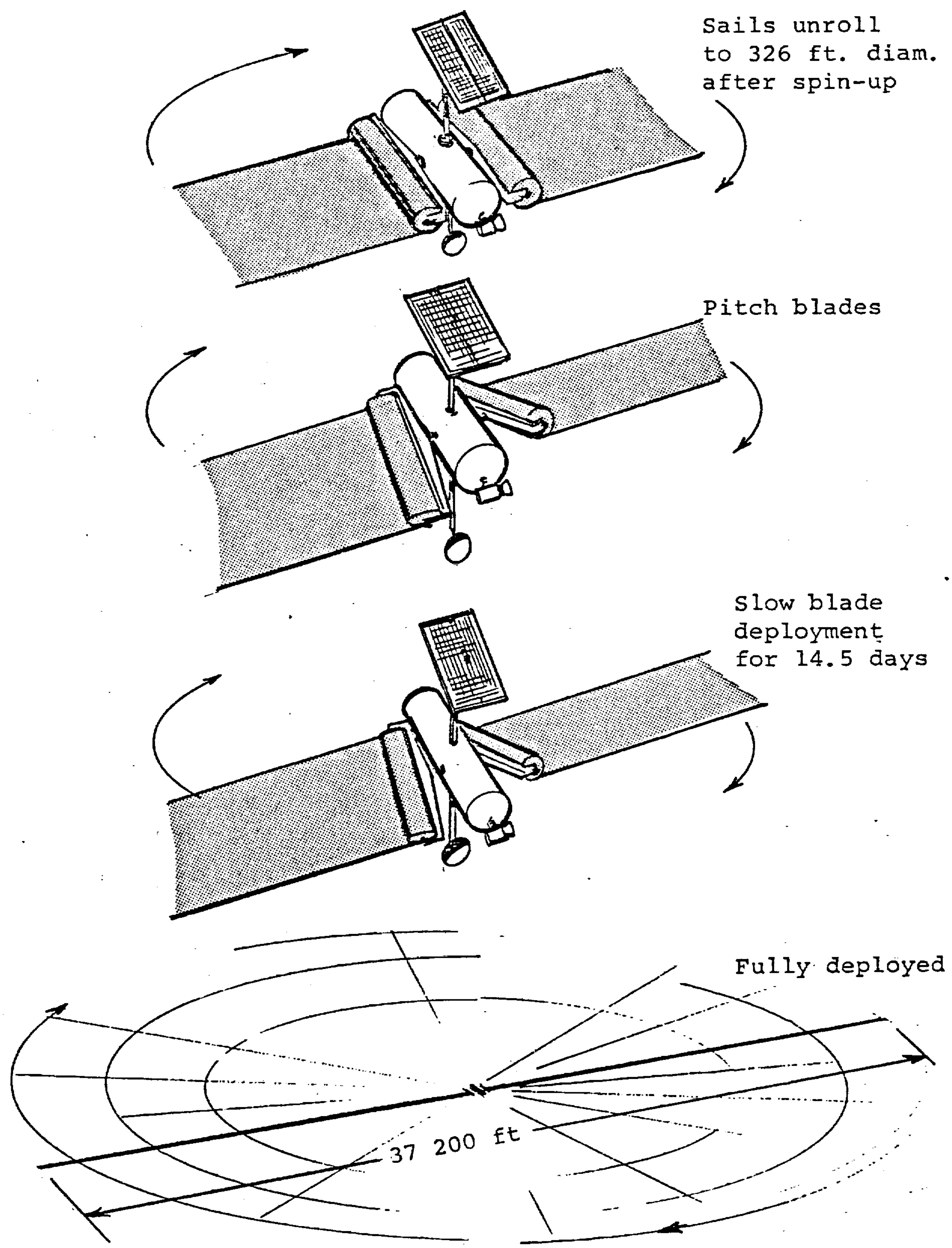

Figure 1. Deployment Sequence

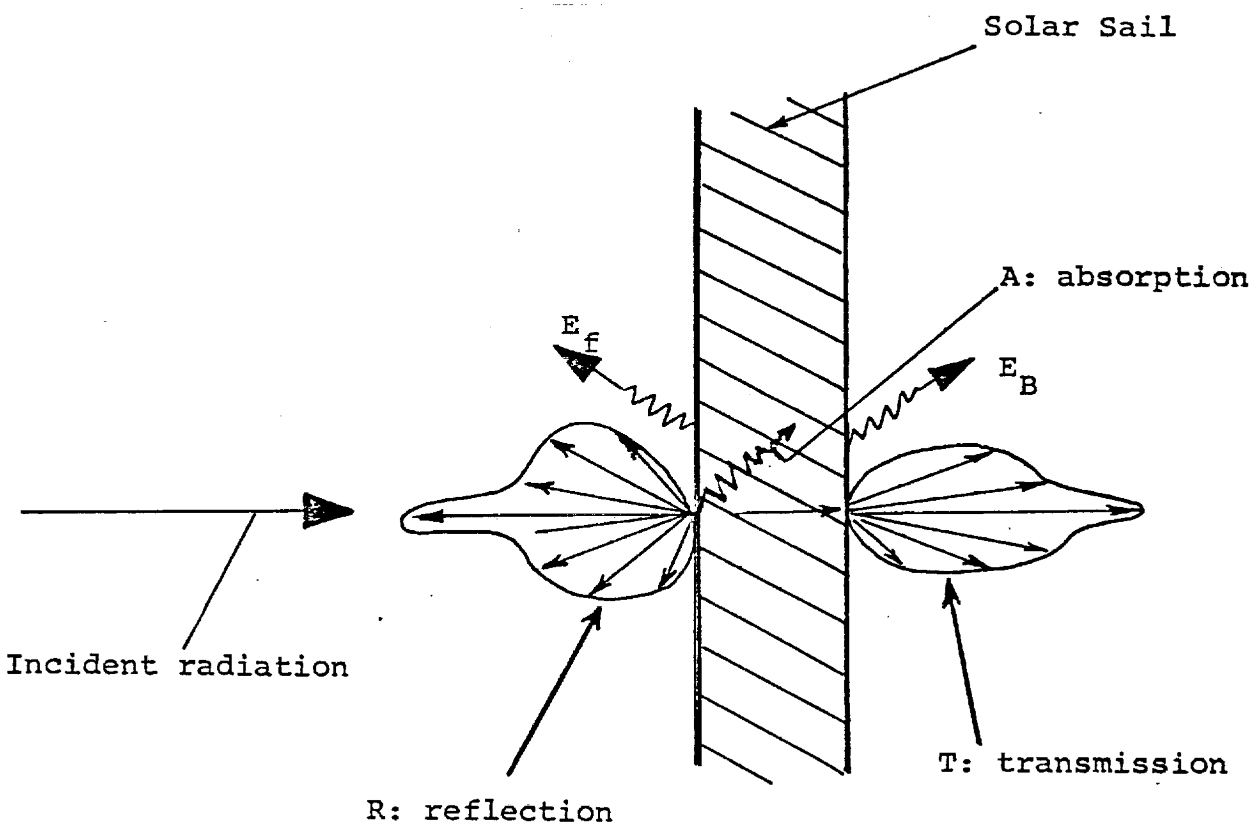

Figure 2. Energy Penetration of Incident Radiation

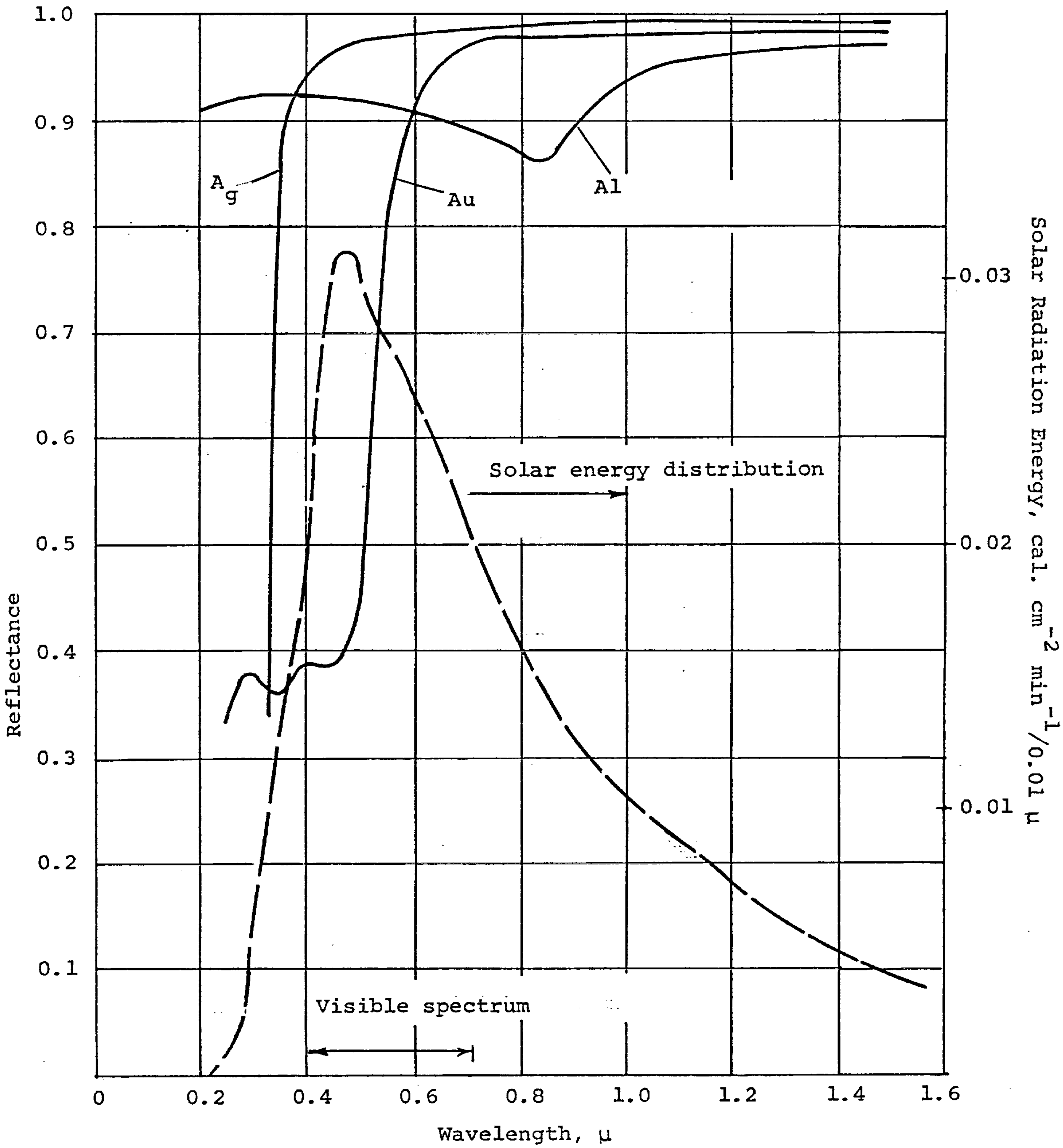

Figure 3. Reflectance of Deposited Metal Films and Solar Spectral Energy

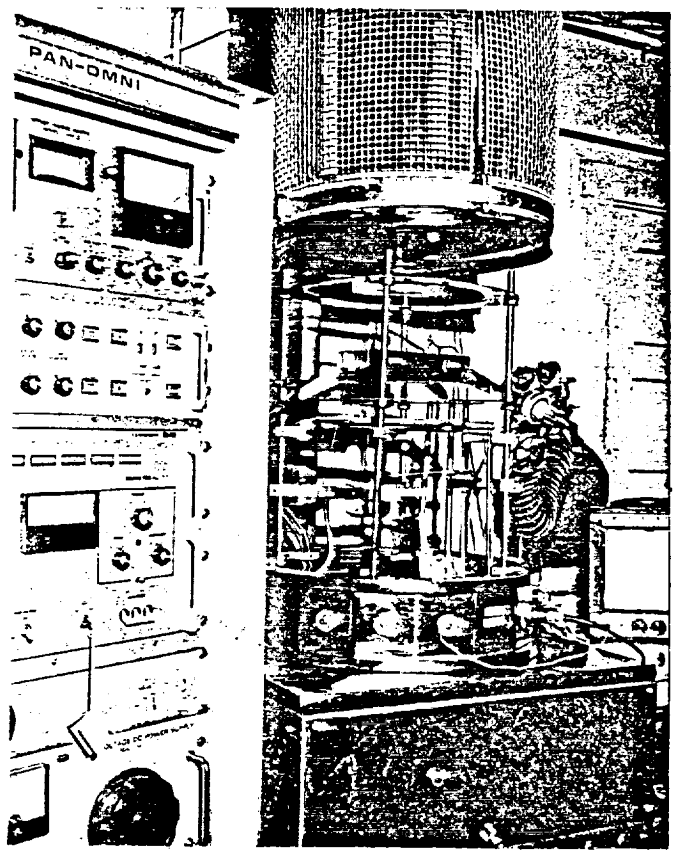

Figure 4. Vapor-Deposition Equipment

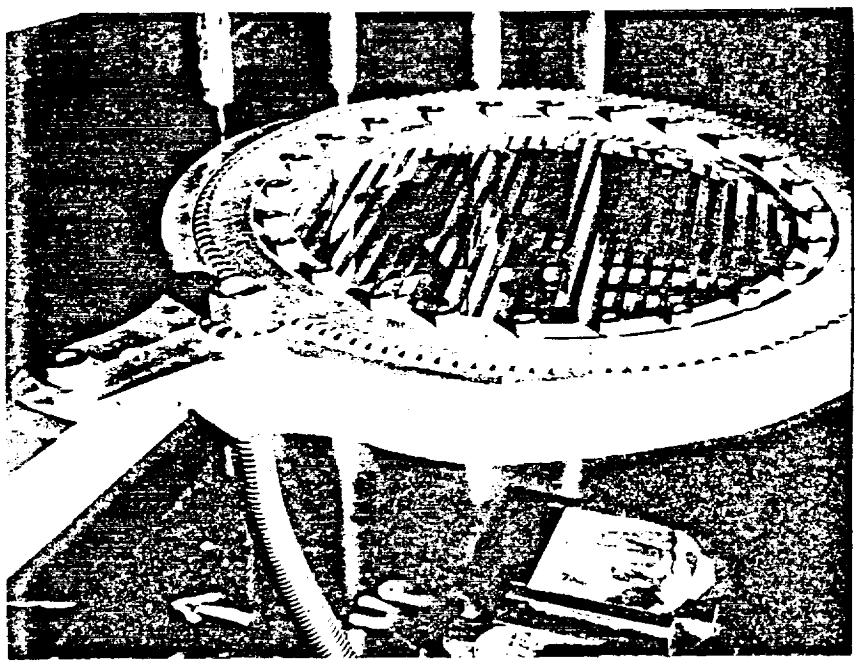

Figure 5. Multiple Strip Mask